Relay Communications Support to the ExoMars Schiaparelli Lander

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Abstract—**The European Space Agency's ExoMars Trace Gas Orbiter (TGO) arrived at Mars on October 19, 2016, three days after releasing the Schiaparelli Lander on a ballistic trajectory to Meridiani Planum. During the separation event, and subsequently during Schiaparelli's Entry, Descent, and Landing (EDL), the NASA-provided Electra UHF payload onboard TGO was used to record signals from the Schiaparelli Lander for post-processing on the ground to recover both tracking of the lander's carrier signal and reconstruction of the lander's 8 kb/s telemetry. In addition, ESA's Mars Express orbiter also recorded the Schiaparelli signal, with ground post-processing providing independent tracking of the lander carrier signal, and the Giant Metrewave Radio Telescope near Pune, India was configured to provide real-time detection of the lander carrier signal. While an anomaly in the latter stages of EDL led to loss of the lander, these critical event data sets, and in particular the telemetry reconstruction enabled by the TGO Electra recording, proved essential in enabling detailed diagnosis of the anomaly. And while the loss of the lander during EDL precluded the planned surface relay operations, the preparations for that activity provide important lessons learned for future Mars relay support scenarios.**

TABLE OF CONTENTS

1. INTRODUCTION

On October 16, 2016, the European Space Agency's ExoMars Trace Gas Orbiter (TGO) released the Schiaparelli Lander on a Mars-impacting trajectory. Three days later, on October 19th, the Schiaparelli Lander arrived at Mars, with the goal of demonstrating Entry, Descent, and Landing (EDL) technologies for future ESA missions.

EDL is a challenging and high-risk mission phase. Accordingly, both NASA and ESA have established policies to ensure the capture of critical event communications during EDL, including both radio metric tracking data and, when possible, actual EDL vehicle telemetry, at rates sufficient to support diagnosis of any anomaly that might lead to mission loss during the EDL phase. For the Schiaparelli EDL technology demonstration, acquisition of such tracking and telemetry data was critical to ensure that the EDL systems could be evaluated, even in the event of a mission-ending anomaly, and that any such anomaly could be reconstructed and diagnosed, enabling corrective actions for future missions.

For Schiaparelli's EDL, robust critical event coverage was achieved over multiple paths. While conducting its own Mars Orbit Insertion (MOI), TGO also acquired high-rate engineering telemetry from the lander throughout EDL. In addition, ESA's Mars Express Orbiter was positioned in its orbit to allow reception of the lander's carrier signal, and the

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Giant Metrewave Radio Telescope in Pune, India was instrumented to also receive the Schiparelli carrier signal.

Once on the surface, plans called for Schiaparelli to receive relay support from ESA's Mars Express Orbiter (MEX) and three NASA relay-equipped orbiters - Mars Reconnaissance Orbiter (MRO), Odyssey (ODY), and Mars Atmosphere and Volatile EvolutioN (MAVEN) – each equipped with UHF relay payloads supporting high-rate proximity link communications. (TGO itself was not available to provide relay services during this period, as it entered into a large four-sol elliptical orbit immediately after its MOI.)

In this paper we outline the critical event telecommunication services provided to the Schiaparelli Lander, as well as the plans for relay orbiter support to the Schiaparelli surface mission. Section 2 will provide an overview of the ExoMars mission, including TGO and its Electra UHF relay payload, as well as Schiparelli Lander and its relay communications capability. Section 3 summarizes the capabilities of the NASA and ESA relay orbiters operating at Mars at the time of Schiaparelli arrival. Section 4 will describe the TGO and EDM proximity link designs. In Section 5 we describe the various ground and flight tests conducted in preparation for Schiaparelli relay support. Section 6 describes the specific support to Schiaparelli separation and EDL, while Section 7 addresses the support to Schiaparelli during its surface mission.

2. EXOMARS MISSION DESCRIPTION

The 2016 ExoMars mission is a collaborative effort between the European Space Agenda (ESA) and Russia's Roscosmos space agency. The mission consists of a Trace Gas Orbiter (TGO) spacecraft that will conduct a range of remote sensing scientific investigations from Mars orbit, including sensitive measurements of trace constituents in the Martian atmosphere [1]. TGO also carried an Entry, Descent, and Landing (EDL) Demonstrator Module (EDM), known also as the Schiaparelli Lander, to demonstrate Mars EDL technologies. Figure 1 illustrates TGO shortly after release of the lander.

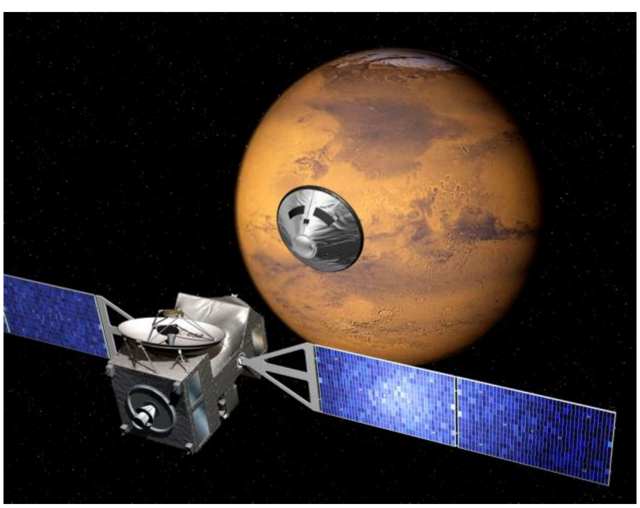

Figure 1: ExoMars Trace Gas Orbiter and Schiaparelli Lander

On March 14, 2016, the TGO spacecraft with the EDM attached launched from the Baikonur launch complex atop a Proton Briz launch vehicle for the ~7-month trip to Mars. On October 16, 2016, three days prior to Mars arrival, TGO released the EDM on a ballistic trajectory towards a landing site in Meridiani Planum (close to where NASA's Mars Exploration Rover Opportunity is continuing its extended mission). After executing a small maneuver to finalize its arrival trajectory, TGO arrived at Mars on October 19, 2016, executing a Mars Orbit Insertion (MOI) burn from 13:05-15:24 UTC that placed TGO in a 4-sol capture orbit.

During TGO's MOI burn, the EDM was scheduled to arrive at Mars within view of TGO, reaching the top of the atmosphere at an altitude of 120 km at 14:42 UTC. The planned EDL timeline included hypersonic deceleration using a heat shield, deployment of a supersonic parachute, and use of retro-propulsion during terminal descent, with landing planned for roughly 14:48 UTC.

NASA made a number of contributions to the 2016 ExoMars mission. In particular, NASA provided ESA with redundant Electra UHF Transceivers to be flown on TGO; these radios are designed to provide relay telecommunication and navigation services to user spacecraft on or near Mars. Similar Electra payloads were previously included on NASA's Mars Reconnaissance Orbiter (MRO) and Mars Atmosphere and Volatile EvolutioN (MAVEN) orbiter. TGO's mission plan called for its Electra payload to capture telemetry and tracking data from the EDM both at the time of its separation from TGO on Oct 16, and during its EDL on Oct 19.

Once the EDM landed, it would be dependent on UHF relay services for all of its telecommunications; it had no direct-to-earth link. TGO's large 4-sol orbit put it at distances much too large to serve as a useful relay asset for EDM. Instead, NASA's relay orbiters MRO, MAVEN, and Odyssey (ODY), along with ESA's Mars Express (MEX) orbiter, were scheduled to provide relay services to the EDM during it surface mission. The battery-powered EDM

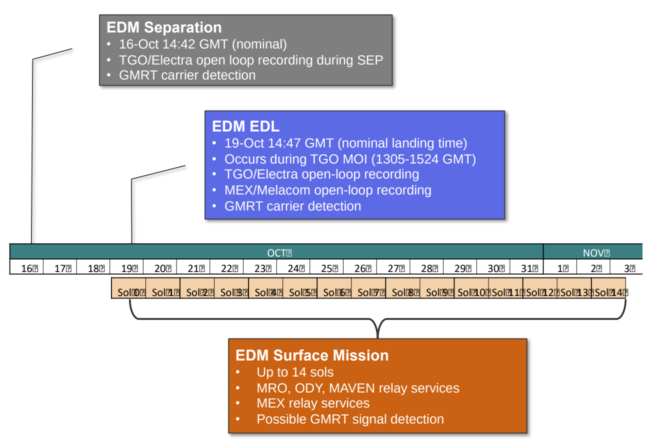

Figure 2: Key phases of EDM relay support

had a nominal design lifetime of 4 sols. NASA agreed to provide relay services for up to 14 sols. Fig. 2 summarizes the three key phases of planned EDM relay support: Separation, EDL, and Surface Operations.

3. CURRENT MARS RELAY NETWORK DESCRIPTION

An evolving international network of relay orbiters at Mars has greatly enhanced Mars exploration by providing high-rate, energy-efficient telecommunication services for small mass- and power-constrained landers and rovers and by enabling capture of high-rate engineering tracking and telemetry during critical events such as entry, descent, and landing [2,3,4,5]. Three NASA orbiters and one ESA orbiter were in operation at Mars at the time of TGO/EDM arrival and provided the basis for EDM surface relay support. We briefly summarize their capabilities here.

NASA's ODY orbiter was launched in 2001 and operates today in a polar, near-circular orbit with an altitude of ~400 km and an ascending node of ~6:45 AM Local Mean Solar Time (LMST). ODY carries a CE-505 UHF transceiver, pre-dating the Electra design, supporting fixed data rates of 8, 32, 128, and 256 kbps. Like the subsequent orbiters, it supports the CCSDS Proximity-1 Space Link Protocol [6,7,8], establishing standardized services to facilitate interoperability across multiple orbiters and landers, including inter-agency cross-support scenarios. ODY is used routinely for relay support to NASA's Opportunity and Curiosity rovers.

ESA's MEX orbiter was launched in 2003. It operates in a highly elliptical orbit, carrying a Melacom UHF relay payload that supports user data rates of up to 128 kbps. Both ODY and MEX offer an open loop recording capability that samples a portion of the UHF spectrum, at one bit-per-sample resolution, which can be post-processed on the ground to reconstruct the spectrum of the received signal. This capability has been used successfully by MEX during the EDL of the NASA Phoenix Lander and Mars Science Laboratory missions to track the UHF carrier signal from the entry vehicle, providing continuous monitoring of the carrier amplitude and frequency, which offers insight into the state of the vehicle throughout EDL. While MEX is not used routinely for Opportunity and Curiosity relay support, ESA and NASA have jointly carried out periodic, few-times-per-year demonstration passes with these rovers to confirm the health of the MEX Melacom relay payload and to maintain relay proficiency.

NASA's MRO orbiter, launched in 2005, operates in a low-altitude, near-circular sun-synchronous orbit, with an ascending node of ~2:50 PM LMST at the time of EDM arrival. It is the first Mars orbiter with the Electra relay payload [9,10], a software-defined radio with significant capability enhancements. MRO Electra supports data rates up to 2 Mbps, and can be configured like ODY and MEX to support a fixed data rate during a given overflight, or can operate in an Adaptive Data Rate mode in which the orbiter continuously monitors the signal strength received from the user spacecraft and, based on that signal amplitude, sends directives to the user spacecraft to adjust its data rate to the optimal rate based on the actual channel characteristics. This allows greatly improved data return, due to the large variations in antenna angles and resulting antenna gain, as

Table 1: Key characteristics of the Mars relay network at the time of ExoMars/TGO arrival

	Mars Odyssey	Mars Express	Mars Reconnaissance Orbiter	MAVEN
Agency:	NASA	ESA	NASA	NASA
Launch:	Apr 7, 2001	June 2, 2003	Aug 12, 2005	Nov 18, 2013
Orbit:	• 400 km circular • 93 deg inclination • Sun-synchronous	• 330 x 10,530 km elliptical • 86.9 deg inclination • Non sun-synchronous	• 255 x 320 km • 93 deg inclination • Sun-synchronous	• 150 x 6,200 km elliptical • 75 deg inclination • Non sun-synchronous
Deep Space Link:				
- Band	• X-band	• X-band	• X-band	• X-band
- Power Amplifier	• 15 W SSPA	• 65 W TWTA	• 100 W TWTA	• 100 W TWTA
- High Gain Antenna	• 1.3 m HGA	• 1.65 m HGA	• 3 m HGA	• 2 m HGA
Proximity Link:				
- Transceiver	• CE-505	• Melacom	• Electra	• Electra (single string)
- Protocol	• CCSDS Proximity-1	• CCSDS Proximity-1	• CCSDS Proximity-1	• CCSDS Proximity-1
- Antenna	• Quadrifilar Helix	• Patch Antennas (2)	• Quadrifilar Helix	• Quadrifilar Helix
- Forward Link				
- Frequency	• 437.1 Mhz	• 437.1 Mhz	• 435-450 MHz	• 435-450 MHz
- Data Rate	• 8, 32 kbps	• 8 kbps	• 8, 32, 128 kbps	• 8, 32, 128 kbps
- Coding	• Uncoded	• Uncoded	• (7,½) Convolutional	• (7,½) Convolutional
- Return Link				
- Frequency	• 401.585625 MHz	• 401.585625 MHz	• 390-405 MHz	• 390-405 MHz
- Data Rate	• 8, 32, 128, 256 kbps	• 2, 4., …, 128 kbps	• 1, 2, 4, …, 2048 kbps	• 1, 2, 4, …, 2048 kbps
- Coding	• (7,½) Convolutional	• (7,½) Convolutional	• (7,½) Convolutional	• (7,½) Convolutional, LDPC
- Other	• 1 bit-per-sample open loop recording	• 1 bit-per-sample open loop recording	• 8-bit I/8-bit Q open loop recording • Suppressed Carrier Modulation • Adaptive Data Rates	• 8-bit I/8-bit Q open loop recording • Suppressed Carrier Modulation • Adaptive Data Rates

well as slant range, during each geometric overflight. Finally, Electra offers a higher-fidelity open-loop recording capability than the transcievers on ODY and MEX, with 8-bit I&Q samples, enabling ground post-processing to fully demodulate a user telemetry stream from the recorded signal, in addition to reconstructing the user carrier.

Table 1 summarizes the key characteristics of this Mars relay network, at the time of arrival of the ExoMars mission.

4. TGO AND EDM RELAY SYSTEM DESCRIPTION

TGO carries a pair of NASA-provided flight-redundant Electra UHF transceivers, functionally identical to the Electra transceiver onboard the MAVEN orbiter. On TGO, each Electra transceiver is connected to its own UHF quadrifilar helix antenna, with an on-boresight gain of 6 dBic and a 3 dB beamwidth of +-40 deg. During the EDM's Separation and EDL, TGO's Electra was configured to capture an open-loop recording of the EDM UHF transmission, as described in Section 6 below.

The EDM UHF system is based on a QinetiQ UHF transceiver. The EDM transceiver operates at fixed frequencies, with a forward link operating at 437.1 MHz and a return link at 401.585625 MHz. With a nominal transmitter power of 4.8 W, the EDM transceiver supports return link data rates of 8 – 1024 kbps, in powers of 2, with optional (7,½) convolutional coding; the forward link operates uncoded, with rates of 8-64 kbps (again in powers of 2). Both residual carrier and suppressed carrier modulation types are supported, and the transceiver supports Adaptive Data Rate operations with Electra-equipped orbiters.

During Separation, and subsequently during the first part of EDL, the EDM transmitted via a Backshell Low Gain Antenna (LGA), a UHF patch antenna mounted on the base of the entry vehicle backshell. Based on its location on the backshell, the antenna provides a gain of 1-2 dBic in the anti-velocity direction, with strong azimuthal variability relative to the entry vehicle symmetry axis. (At 45 deg from the anti-velocity direction, the gain varies from ~0 dBic to -6 dBic over azimuth.)

After backshell separation, for the remainder of EDL and for the subsequent surface mission, the EDM planned to utilize the Surface Platform LGA, an upward-looking quadrifilar helix antenna with on-boresight gain of 6.2 dBic at the 401.585625 return link frequency.

5. VERIFICATION AND VALIDATION RELAY TESTING

Thorough verification and validation (V&V) testing is essential in order to establish interoperability of the UHF transceivers and the end-to-end flight-ground data paths supporting lander-orbiter relay services. This is particularly true for links between spacecraft equipped with proximity link transceivers provided by separate agencies and implemented by separate organizations. To this end, a dedicated series of interoperability tests were conducted at Lockheed Martin Space Systems in Denver, CO from 20 July – 12 August, 2015. During this test campaign, an EDM test set consisting of the QinetiQ EDM transceiver engineering qualification model, along with the EDM on-board computer functional unit model, were successively integrated with the MRO, MAVEN, and ODY orbiter testbeds.

These tests exercised all the planned relay link configurations for the EDM-MRO/MAVEN/ODY links. MRO and MAVEN tests completed nominally; however, two interoperability issues were discovered on the EDM-ODY link. First, the EDM transceiver utilizes a Proximity-1 Transfer Frame size of 1124 bytes, which is incompatible with the ODY's 1024-byte Transfer Frame length. Second, a single bit in the ODY CE-505 transceiver hail sequence, related to the coherency configuration of the link and typically not utilized by NASA landers, was set to a value not expected by the EDM transceiver, causing the orbiter hail to be rejected. Both of these issues precluded use of the CCSDS Proximity-1 link protocol on the EDM-ODY link. Instead, based on these tests, ODY relay support to the EDM was limited to the unreliable bitstream mode. In this mode the Proximity-1 link layer protocol does not function; instead, the EDM simply initiates a simplex return link at a pre-scheduled time, and ODY demodulates the received bitstream. The full-duplex reliable Proximity-1 protocol is not used, and as a result it is possible for there to be data gaps and/or errors during periods.

One other interoperability issue for NASA relay orbiter support to the EDM was discovered later, in Aug 2016. During testing in preparation for an operations simulation test at ESOC, an ESA-supplied EDM data file was transmitted in the MRO testbed in Denver, with the MRO ground support equipment configured to emulate the EDM. With the link configured for Adaptive Data Rate with suppressed carrier modulation, this particular file stalled and failed to be successfully transferred across the simulated proximity link. Subsequent investigation revealed that this file included extended periods of repeating, non-random data patterns; because the EDM transceiver did not incorporate a scrambler, this created a vulnerability of the link to such non-random data patterns when operating in suppressed carrier mode (only available on the Electra-equipped MRO and MAVEN links). It was not expected that actual EDM flight data would exhibit such non-random data patterns; nonetheless, to mitigate risk, a subset of the MRO and MAVEN passes were converted to residual carrier modulation, which also constrained them to be configured as fixed-rate passes.

ESA also performed independent compatibility testing of the EDM-MEX link in November 2015, uncovering a compatibility issue that was addressed via a MEX MELACOM software patch that was uploaded to the orbiter in April 2016. The MEX project also conducted a successful full test run of the planned EDM EDL support in conjunction with MSL, in which MEX recorded a modulated carrier broadcast by the Curiosity Rover, simulating the EDM's EDL transmission.

Thorough testing was also performed to validate the performance of the NASA-supplied Electra UHF Transceivers on TGO, and to ensure readiness for the use of the TGO Electra payload to acquire Schiaparelli's UHF transmission during separation and EDL. In addition to pre-launch Electra tests in ESA's ExoMars testbed, a number of in-flight tests were performed during the cruise to Mars.

Initial Electra post-launch commissioning tests were performed during two test windows, on Apr 1-2 and Jun 16, 2016. These tests exercised Electra's "relay loopback" mode, in which a small amount of the Electra transmit signal is leaked back into the receive path, enabling an end-to-end test of Electra's relay functionality. Additional "bit error rate (BER) loopback" testing was performed in this mode to vary the received signal level and calibrate the receiver thresholds (i.e., the received power level required to attain a given bit error rate). These tests also exercised Electra's open-loop recording capability, and confirmed that with science instruments off, there was no indication of any significant levels of electromagnetic interference (EMI) that would degrade the Electra thresholds.

Subsequent tests on Apr 4-7 and Apr 18 repeated the BER loopback tests and open-loop recordings as individual science instruments were powered on, confirming that none of the TGO science instruments generated any significant levels of EMI that would impact TGO Electra performance. This is an important and encouraging result for the long-term use of TGO as a relay asset, once it reaches its final science orbit in 2018.

On Apr 8 and Jun 17, tests were performed in which the EDM transmitted 8 kbps telemetry on its UHF link, and TGO's Electra UHF Transceiver acquired an open-loop recording of the EDM signal for subsequent ground post-processing. These tests successfully validated the end-to-end data path that the EDM would us on separation day (Oct 16) and landing day (Oct 19).

Finally, on Aug 11 and Sep 21, the TGO Electra was operated with the same temporal sequence that would be used on Oct 19, in a flight-like dress rehearsal of landing day. For the Sep 21 test, periods of EDM transmission were also included, with ground post-processing verifying the end-to-end relay path.

6. Critical Event Communication Support During EDM Separation and EDL

On Oct 16, 2016, the Schiaparelli Lander separated from the TGO spacecraft at 14:42 UTC. The lander transmitted 8 kb/s telemetry over its UHF link throughout separation, and TGO's Electra payload was configured to acquire an open-loop recording of the EDM signal during the separation event, with a sampling rate of 128 kHz, sufficient to capture the EDM's telemetry spectrum. In addition, the Giant Metrewave Radio Telescope (GMRT) near Pune, India was configured to receive the EDM signal during separation. The GMRT was successful in detecting the EDM carrier during separation, and the Electra open-loop recording was successfully post-processed on the ground, providing telemetry confirming the health of the lander after separation; details on both data paths are provided below. In addition to confirming a successful separation and healthy lander, this support also provided an excellent dress rehearsal for similar support planned for EDL itself.

Three days later, on Oct 19, 2016, TGO and the EDM arrived at Mars. TGO performed a Mars Orbit Insertion burn from 13:05-15:24 UTC to capture into an initial 4-sol orbit. During this MOI burn, and in view of TGO, the Schiaparelli Lander executed its EDL. Figure 3 illustrates the geometry at Mars during Schiaparelli's EDL.

Table 2 summarizes the planned timeline of critical event communications during Schiaparelli's EDL on Oct 19. Starting 75 min prior to arriving at the Mars Entry Interface Point, defined as an altitude of 120 km, Schiaparelli transmitted engineering telemetry at a rate of 8 kb/s via its QinetiQ UHF transceiver. This transmission was scheduled to continue until 15 min after the predicted landing epoch of 14:48 UTC. The QinetiQ UHF transceiver was configured with residual carrier, BPSK modulation, with a 60 deg modulation index, at a center frequency of 401.585625 MHz. The information bitstream was encoded with a (7,½) convolutional code.

Table 2: Planned sequence of communications events during Schiaparelli EDL

Time (SCET)	Event
13:22	MEX begins "canister mode" open-loop recording
13:27	EDM begins 8 kb/s transmit
14:16	TGO/Electra begins open-loop recording
14:32	TGO/Electra reset; close first open-loop recording file and open second file
14:42	EDM Entry Interface Point (predicted, 120 km altitude)
14:48	EDM landing (predicted)
14:54	TGO/Electra ends open-loop recording
15:02	EDM ends 8 kb/s transmit (L + 15 min)
15:07	MEX ends "canister mode" open-loop recording

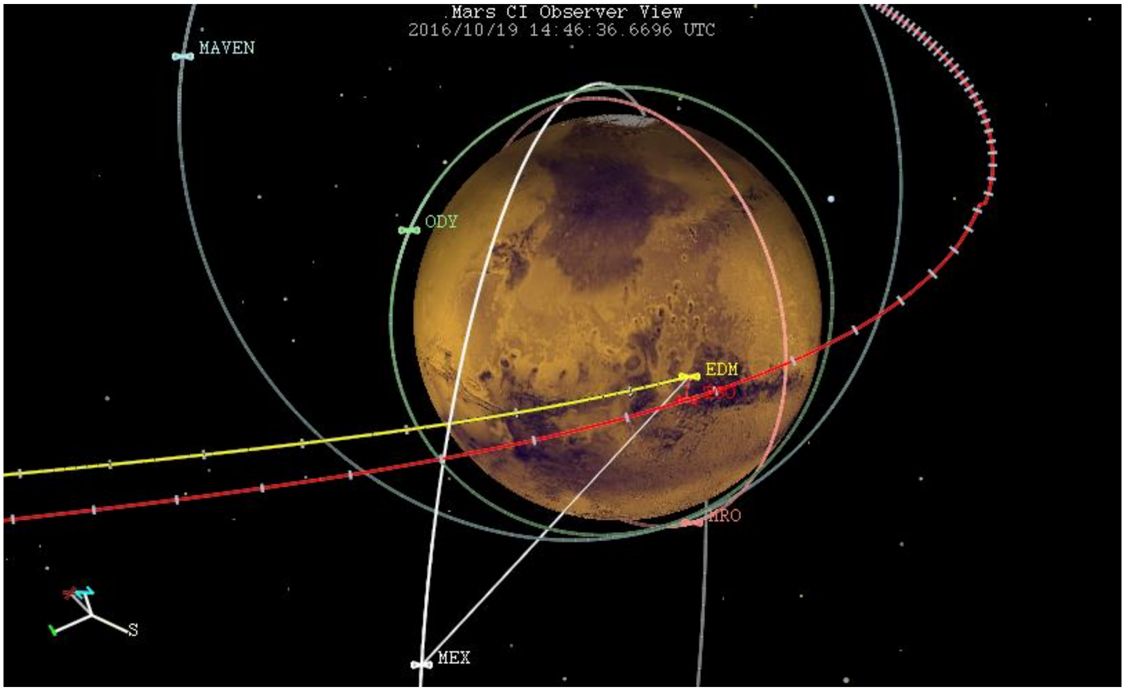

Figure 3: Geometry of EDM arrival during EDL on Oct 19, 2016, showing critical event relay links to TGO and MEX.

TGO, Mars Express, and Earth were all in view of the lander throughout its EDL trajectory. The EDL communications strategy took advantage of links to all three locations, with each offering varying combinations of received signal strength, recovered information, and processing latency. TGO represented the primary EDL communications path, receiving and recording the full Schiaparelli UHF signal for post-EDL transfer to the ground, where post-processing yielded the time history of the EDM carrier frequency, revealing information on line-of-sight velocity based on the observed Doppler shift, and also recovered the full EDM telemetry stream. However, due to the large size of the recording and the required time to downlink the file to Earth and for ground signal processing, the TGO products were not available until roughly 12 h after EDL. MEX made a separate, lower-fidelity recording of the EDM UHF signal. This recording only allowed recovery of the EDM carrier frequency history, not the full telemetry stream; however, the lower data volume associated with this recording allowed this product to be produced and available on the ground roughly 80 min after landing. Finally, the direct-to-Earth link to GMRT allowed monitoring of the Schiaparelli EDL carrier signal effectively in real-time, after accounting for the one-way light time of 9 m 47 s at the time of arrival. This path provided the lowest-latency information on the status of Schiaparelli's EDL, albeit at very low signal-to-noise levels.

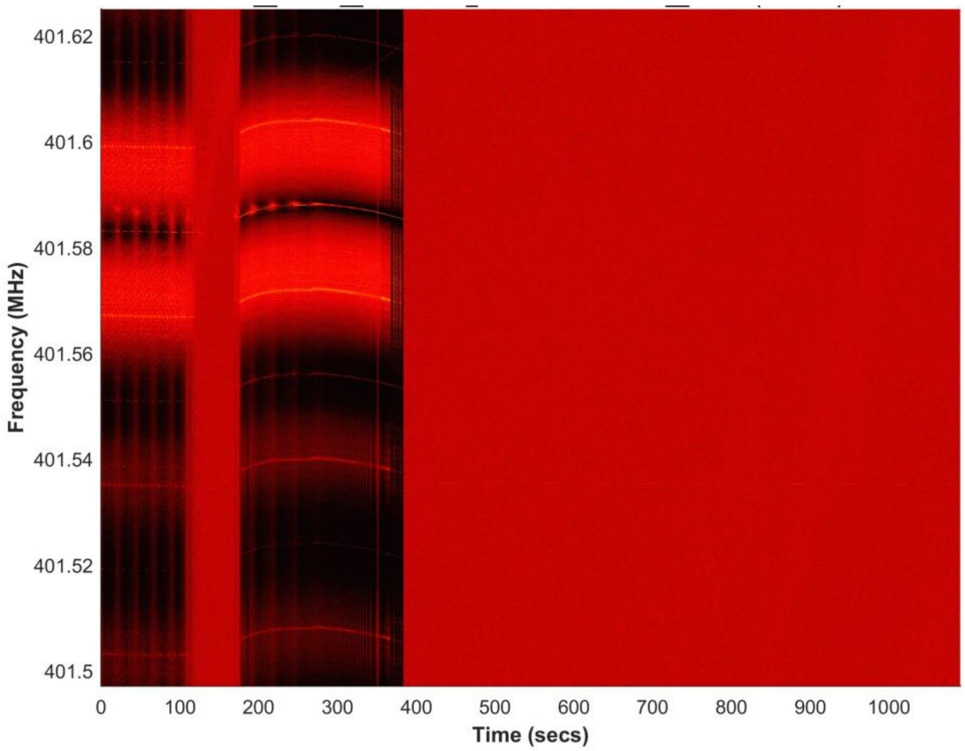

Figure 4: Spectrogram of EDM UHF signal as received by TGO Electra during EDL. Time origin corresponds to the epoch 14:40:59 UTC.

The other available Mars relay orbiters – MRO, Odyssey, and MAVEN – were not positioned to allow visibility of Schiaparelli's EDL. (MRO's orbit plane could have supported partial EDL coverage, but ESA requested that MRO instead be phased in its orbit to optimize post-landing overflight geometries for the first few sols of surface operations; the resulting MRO true anomaly did not provide geometric contact during EDL.)

In the remainder of this section we summarize the results obtained on each EDL communications path.

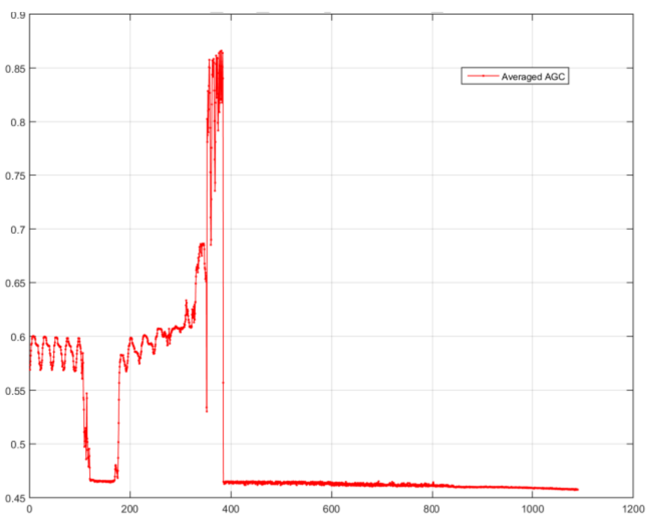

Figure 5: TGO Electra Automatic Gain Control telemetry during Schiaparelli EDL, indicating the strength of the received lander signal. Time origin corresponds to the epoch 14:40:59 UTC.

Trace Gas Orbiter/Electra

TGO was conducting its MOI burn throughout the period it was receiving Schiaparelli's UHF transmission. This constrained the orbiter's attitude to orient the propulsive burn in the anti-velocity direction. The roll angle about this axis was then optimized to maximize the UHF antenna gain in the direction of the lander during its EDL trajectory.

TGO's Electra payload was configured to acquire an open-loop recording of the EDM UHF signal at its maximum sampling rate of 128 kbps. In this open-loop recording mode, Electra downconverts the UHF signal to baseband, Nyquist-filters the baseband signal and then acquires in-phase and quadrature (I&Q) samples of the band-limited baseband signal, at a resolution of 8 bits per sample. Electra's recording began at 14:16 UTC and extended until 14:54 UTC. Because of the large size of the open-loop recording and the resulting long latency in downlinking that file to Earth, and because there was higher risk and thus higher interest in the post-entry phase of the EDL event, Electra's recording was broken into two separate files, with a brief reset at 14:32 UTC at which point the first pre-entry file was closed and the second file, which continued through entry, descent, and landing, was opened. After EDL was complete, and after TGO completed its MOI burn and re-established HGA downlink to Earth, the two files were downlinked to Earth in reverse order, with the higher-priority atmospheric phase file returned first.

Both ESA and NASA developed post-processing software to track the carrier phase of the EDM transmission and to demodulate the EDM telemetry stream. Both analyses obtained consistent results; we report here on the NASA analysis products.

Figure 4 represents a spectrogram of the received EDM signal, mapped to the UHF sky frequency, while Figure 5 illustrates the Electra Automatic Gain Control telemetry during this same period, reflecting the received signal strength. The time origin for this plot corresponds to an epoch of 14:40:59 UTC. The first ~100 s of the plot corresponds to the final pre-entry phase of the EDM trajectory. One can clearly see the 8 kb/s telemetry spectrum centered around the carrier frequency of ~401.583 MHz. A temporal modulation in the amplitude of the signal, with a period of ~20 s, is due to the residual spin rate of the entry vehicle and the resulting variation in lander UHF antenna gain in the direction of TGO.

After a little over 100 s, the signal fades - as expected - due to buildup of plasma around the entry vehicle during the hypersonic phase of entry. This signal outage lasts for roughly one minute, after which the signal returns and displays Doppler signatures associated with atmospheric deceleration. At around 350 s there is a momentary loss of signal, believed to be due to backshell separation, when transmission switched from the backshell antenna to the lander's helix antenna, briefly blocked by the separating backshell itself. Roughly 30 s later, the signal is unexpectedly and prematurely lost.

A software phase-locked loop was used to track the carrier signal in this open-loop recording; the resulting carrier frequency observable, during periods of solid loop lock, is shown in Figure 6. Here one can also see the signature of parachute deployment at roughly 14:45:25.

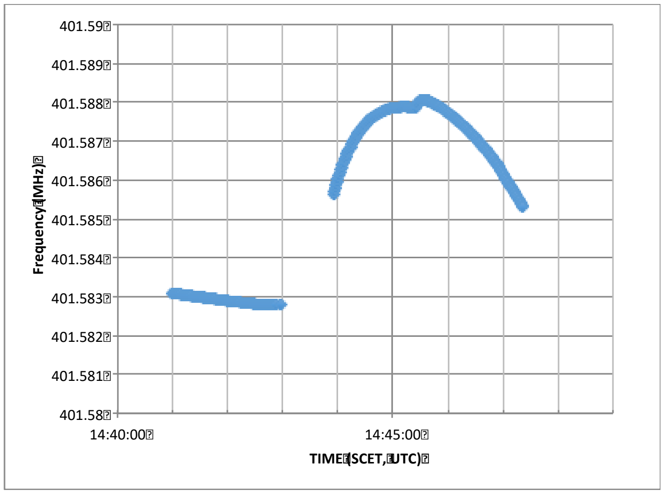

Figure 6: Recovered EDM carrier frequency from TGO Electra open-loop recording, during atmospheric phase of EDL.

Table 3: Recovered Data Statistics from the TGO Electra Open-Loop Recordings of the Schiaparelli EDL

	Open-Loop Recording #1 (pre-entry phase)	Open-Loop Recording #2 (entry phase)
Recording Duration:	866 s	1090 s
# of Recovered Frames:	629	260
# Frame CRC Errors:	27	13
Data Volume (Valid Frames):	5.428 Mb	2.227 Mb

The post-processing software also performed demodulation of the Schiaparelli 8 kb/s telemetry stream throughout the two open-loop recordings. This included decoding of the (7, ½) convolutional code applied to the EDM bitstream. The resulting bitstream was then analyzed to identify the CCSDS Proximity-1 frame structures created by the EDM's QinetiQ UHF transceiver. Each Proximity Link Transmission Unit (PLTU) includes a 24-bit Attached Synchronization Marker (ASM), followed by a Version-3 Transfer Frame containing EDM data, and closing with a 32-bit Cyclic Redundancy Check (CRC). The CRC and the Frame Sequence Number field in each transfer frame header provide means to identify valid frames, as well as data gaps and frames corrupted with bit errors. Table 3 summarizes the data recovered from the two Electra open loop recordings. In total, over 7.6 Mb of telemetry was obtained from the Schiaparelli Lander, including over 2.2 Mb from the second recording that encompassed the post-entry phase of EDL, up until the loss of signal.

Mars Express

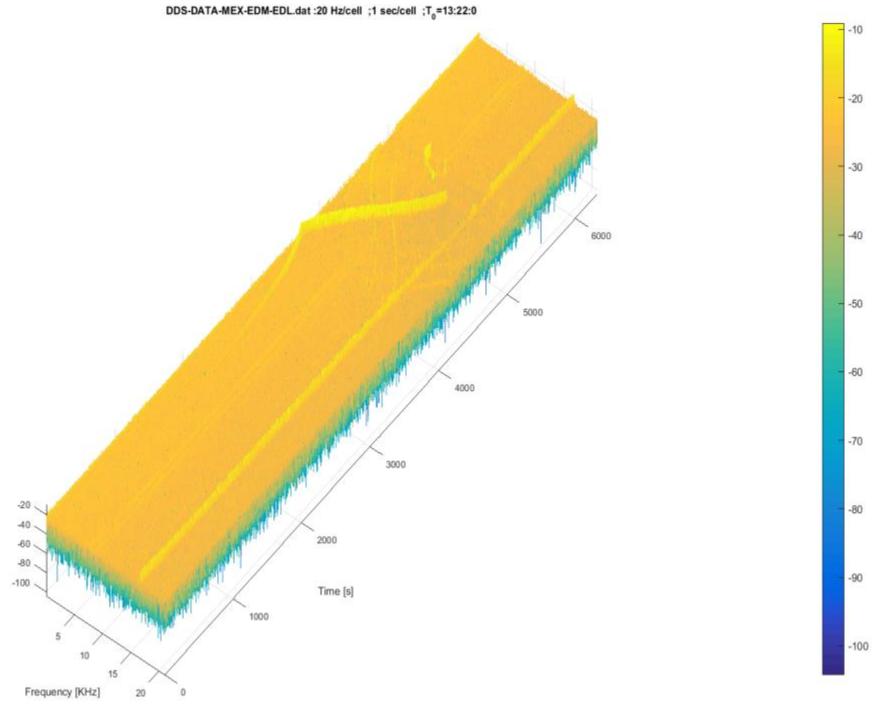

Figure 7: 3-D "waterfall" plot of Schiaparelli UHF signal spectrum vs. time, as recovered from the MEX canister mode recording. The time t=0 s corresponds to the epoch 13:22 UTC.

MEX was re-phased in its orbit in order to provide optimal geometry for viewing the Schiaparelli EDL. MEX was at one point scheduled to perform EDL support for both the EDM and NASA's InSight lander, which originally would have arrived in mid-September. The initial orbit re-phasing called for a maneuver in Feb 2016 which would permit the EDL of InSight to be monitored followed by a second maneuver at the end of September to optimise for the EDM. Following the launch delay to InSight, this second manoeuvre was brought forward to July 2016 with the view of saving fuel. As the intention was for an open loop recording of the EDL phase, which is known to work at long slant ranges, the geometry was optimised to give the best elevation at the time of landing.

A software patch was generated and applied to MELACOM in April 2016 following an issue identified during the MEX-EDM UHF compatibility tests carried out in November 2015.

A full test run of the EDL support was carried out in conjunction with MSL, where MEX recorded a modulated

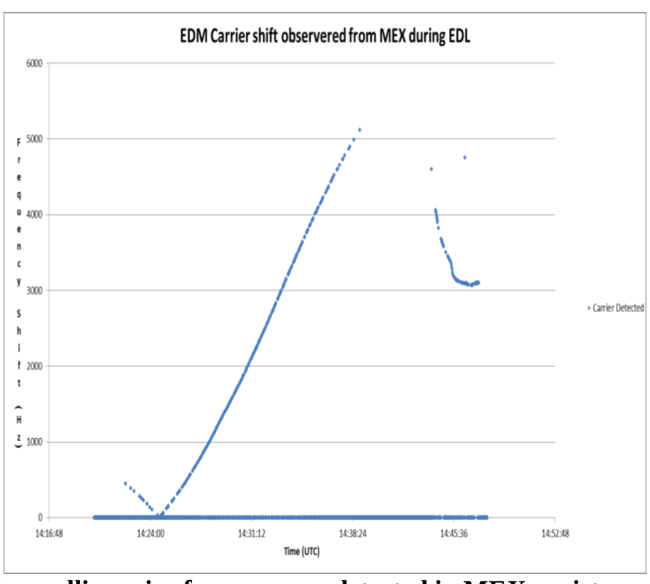

Figure 8: Schiaparelli carrier frequency as detected in MEX canister mode recording

carrier broadcast by the rover.

In canister mode, a continuous stream of 1-bit samples of the raw TTL video output of the receiver is generated. With this limited sampling resolution, telemetry cannot be extracted from the open loop recording produced by Melacom; only carrier detection is possible from which the Doppler can be reconstructed.

For previous EDL supports, MEX had only recorded for approximately 20 minutes; however, given the low data volume produced by Melacom's open loop mode, it was decided that MEX would attempt to record the carrier coming from the EDM from 5 minutes prior to wake up until 5 minutes after the scheduled post-landing hibernation entry. This represented a total duration of 106 minutes, during which time MEX would have to continuously slew to keep the Melacom antenna boresight targeted at the EDM. This targeting was handled via a custom pointing sequence created by ESOC's flight dynamics team. MELACOM was switched on 2hrs 14m prior to the start of the recording to give the receivers chance to reach a stable temperature. This time was selected as the Melacom housekeeping packet store has sufficient capacity for approximately 4.5 hrs of operation. Thus the total Melacom on time for the EDL support was set to 4 hrs to allow for sufficient margin.

The raw recording was post-processed on the ground using a toolkit constructed in Matlab to generate a "waterfall" plot – or spectrogram - of signal strength as a function of time and frequency (Figure 7), and a plot of carrier detection which shows the frequency shift (Figure 8).

The reconstructed plot of the detected carrier frequency shows initial acquisition of signal prior to atmospheric entry, followed by plasma blackout, parachute deployment, and unexpected early loss of signal. The carrier detection plot showed AOS at 14:21:53 UTC which is approximately 55 minutes after the EDM wakeup. However, examining the waterfall plots, it is possible to first see a weak signal starting to appear at approximately 14:03. This later-than-expected AOS is likely to be due to the large, 23,000-km line-of-sight distance between the two spacecraft at the time of EDM wake-up. This represented the furthest line-of-sight distance from a signal source ever attempted with Melacom. The weak signal starts to appear at approximately 10,500km range, which is consistent with previous long-range carrier detection tests of Melacom with MER-B performed ahead of the arrival of MSL.

The plasma blackout is longer than seen on GMRT and from TGO; however, a similar result was observed during the MSL EDL with the blackout observed by Melacom being larger than the data relayed by ODY. It is not clear at this time what the reason for this extended blackout period is. MEX reported final LOS from EDM at 14:47:23 UTC.

Examination of the 3d waterfall plot prior to EIP shows an oscillation in signal strength approximately every 20 seconds. This is consistent with the 3 rpm rotation rate of the EDM.

Giant Metrewave Radio Telescope

The Giant Metrewave Radio Telescope (GMRT) is an array of thirty 45-m antennas, located in Pune, India and operated by the National Centre for Radio Astrophysics. In support of the ExoMars project, NASA's Deep Space Network made arrangements to configure GMRT to receive and detect the Schiaparelli UHF carrier signal. A sub-array of 12 of the antennas was utilized during the EDL event, representing an effective collecting area equivalent to a single 156-m diameter antenna. (For the separation event three days earlier, a slightly larger sub-array of 16 antennas was used.) The predicted signal level was much too low to allow recovery of the Schiaparelli data stream; instead, the objective was simply detecting the lander's residual carrier signal, which was predicted to be just a few dB above the array's noise floor.

Figure 9 illustrates the observed Schiaparelli carrier frequency, after removal of an *a priori* model based on the predicted lander trajectory. This information was made available via Internet from GMRT to ESOC during the landing event. The GMRT analysis provided confirmation of the aliveness of the lander through entry, peak heating, and subsequent parachute deployment. However, at 14:57:08 UTC (Earth Receive Time), the signal was unexpectedly lost. This epoch corresponds to a Spacecraft Event Time (SCET) of 14:47:21, well in advance of the predicted touchdown time of 14:48:33.

7. EDM SURFACE RELAY SUPPORT

Once on the surface, NASA's MRO, ODY, and MAVEN orbiters, as well as ESA's MEX orbiter, were scheduled to provide relay telecommunication services to the EDM. The first post-landing pass was supported by MRO on Oct 19th at 16:53:56 UTC, roughly two hours after landing. This first pass was conservatively configured for a modest fixed data

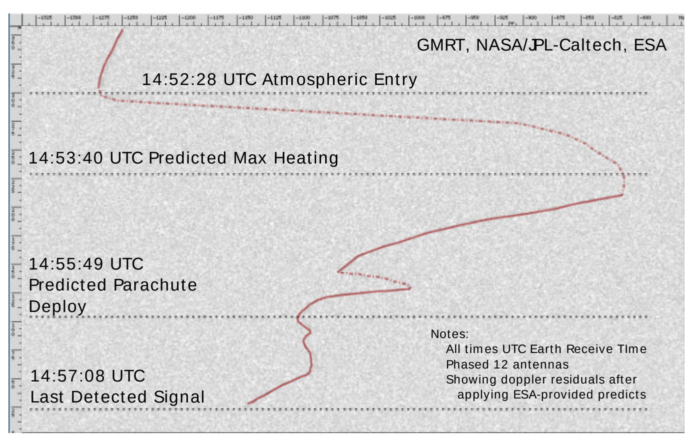

Figure 9: Received Schiaparelli UHF carrier frequency at GMRT, up to loss of signal at 14:57:08 UTC (Earth Receive Time)

rate of 32 kbps on the return link in order to ensure significant link margin. MRO's downtrack orbit position was controlled in the months leading up to EDM arrival in order to ensure optimal MRO overflight geometry for the first few sols of EDM surface operations. Specifically, the MRO downtrack was required to be within ±5 min of an ESA-specified value for the third MRO overflight, which resulted in this third MRO overflight passing almost directly over the landing site. The final MRO orbit met this requirement to well under 1 min of downtrack position control.

Over the successive 14 sols, a total of 46 relay passes were scheduled, with 32 passes by the three NASA orbiters. By spreading the relay service across all available orbiters, the resulting relay support plan was robust to the possibility of any individual orbit being unavailable due to an orbiter safing event. In addition, the full set of supported passes included a variety of relay configurations, again increasing robustness against any potential interoperability issues. For instance, MRO and MAVEN passes included a mix of both Adaptive Data Rate passes and Fixed Rate passes. In addition, three open-loop passes were scheduled on MRO. These passes did not involve any orbiter hailing sequence of Proximity-1 link layer protocol; instead, the EDM was simply scheduled to transmit an 8 kbps telemetry stream during the MRO overflight, and MRO's Electra payload acquired an open-loop recording for post-processing at ESOC to recover the EDM telemetry stream. Similarly, MEX scheduled a mix of passes, with five fixed-rate Proximity-1 passes scheduled, along with nine additional passes configured for open-loop recordings to simply attempt to detect a signal from the lander; these latter passes were all scheduled during periods when GMRT also had visibility of the landing site, allowing parallel signal detection on the direct-to-Earth link. Finally, due to the interoperability issue discovered in pre-flight testing, all of the ODY passes were configured for unreliable bitstream mode, also avoiding any potential Proximity-1 link layer interoperability issues. Table 4 summarizes the full set of planned surface relay contacts.

A key aspect of the EDM relay operations was the use by all the participating missions of the Mars Relay Operations Service (MaROS), NASA's online tool for scheduling relay passes [11]. Use of the MaROS system ensured clear cross-project communications on requested EDM relay link configurations and NASA orbiter relay commitments, provided a single operational interface for any forward link EDM command products, and provided a single venue to publish *a posteriori* information on relay pass performance. Data rates for fixed-rate passes were based on *a priori* link analysis, with appropriate link margins included.

On the actual day of landing, all that was known immediately after EDL was that the Schiaparelli signal had been lost prematurely, prior to the expected touchdown epoch. Accordingly, there was great interest in the initial surface relay passes. The first MRO pass, roughly two

Table 4: EDM Relay Pass Requests

Orbiter	# Passes	Comments
MRO	18	• 3 Adaptive Data Rate Prox-1 • 12 Fixed Rate Prox-1 • 3 Open-Loop Record (post-process to recover EDM 8k TLM)
MAVEN	6	• 5 Adaptive Data Rate Prox-1 • 1 Fixed Rate Prox-1
ODY	8	• All passes Fixed Rate Raw Data Mode
MEX	14	• 5 Fixed Rate Prox-1 • 14 Open Loop Record (post-process to recover EDM carrier)

hours after landing at about 3 PM Local Mean Solar Time (LMST) on the landing sol (Sol 0), resulted in no data received from the lander. Review of the MRO Electra telemetry indicated that the orbiter hailed as scheduled, but that no lander signal was received in response to the hail from the surface, and thus no full-duplex link was established. Over the next ~25 hrs, two additional passes were conducted by MRO: one at ~ 3 AM LMST on the sol after landing (Sol 1) and another at ~3 PM LMST that same sol. These passes also resulted in no detection of any signal from the lander.

On this same sol (Sol 1), additional passes were conducted by MEX, MAVEN, and ODY. MEX conducted an open-loop pass at ~9 AM LMST, with the goal of detecting a scheduled transmission from the lander; GMRT was also listening at this time. Neither MEX nor GMRT detected a signal from Schiaparelli. Later that sol, Proximity-1 passes were conducted by MAVEN (~6 PM LMST) and by ODY (~7 PM LMST); again, neither pass showed any evidence of a signal from the lander.

During the third MRO pass, which overflew the landing site near zenith, MRO imaged the targeted landing site with its CTX and HiRISE imagers. The CTX camera, with a wider field of view, observed several artifacts associated with the landing, including the deployed lander parachute as well as an impact site where the lander appeared to have struck the surface at high velocity [12]. (Subsequent imaging by MRO's HiRISE camera on Oct 25th [13] and Nov 1st [14] provided higher resolution and multi-spectral images of the landing area, clearly showing the lander impact site, the backshell with deployed parachute, and the separated heatshield.)

Based on this evidence, as well as preliminary information from the GRMT, MEX, and TGO critical event data sets, on Oct 20 ESA released NASA from any additional EDM relay support. MEX conducted two additional passes (one open-loop and one Prox-1) prior to the withdrawal of further support requests by the ExoMars project.

Over the subsequent days a clearer picture of the lander anomaly emerged from analysis of the critical event data sets, including both the Doppler information from the TGO, MEX, and GMRT tracking of the EDM UHF carrier signal and from the extensive EDM telemetry recovered from the TGO Electra open-loop recording. While the anomaly investigation is continuing, several preliminary conclusions have been reported [15]. Preliminary analysis suggests that an anomaly in the lander's guidance, navigation and control System led to saturation of the Inertial Measurement Unit (IMU) which tracks lander rotation rates. This saturation resulted in a large error in the lander's onboard estimate of its angular orientation, which led to erroneous interpretation of valid radar altimetry measurements, causing the vehicle to believe it had already reached the surface. This resulted in premature release of the parachute and backshell and a minimal-duration firing of the lander's retropropulsion system. In fact, the vehicle at that point was still at an altitude of 3.7 km, and proceeded to free-fall to the surface.

In addition to shedding light on the root cause of the EDL anomaly, it is important to note that the critical event data also confirmed the nominal execution of many elements of the Schiaparelli EDL system, including performance of the heatshield during hypersonic entry, deployment of the parachute, release of the lander heatshield, and performance of the radar Doppler altimetry system. The successful validation of these EDL technologies is an important dividend of the EDM demonstration, and one which would not have been possible without the critical event coverage provided during EDL.

8. SUMMARY

The relay support to the Schiaparelli Lander EDL demonstration represents a successful step forward in the development of a truly international Mars relay network, for the support of future Mars exploration. Close cooperation between NASA and ESA enabled development of a robust strategy for capture of critical event tracking and telemetry data during Schiaparelli's separation and subsequent EDL, combining support from ESA's TGO orbiter with its NASA-provided Electra relay payload, as well as ESA's MEX orbiter and complementary direct-to-Earth signal detection at GMRT. These critical event data sets have allowed validation of many elements of the Schiaparelli EDL design, and have enabled a preliminary determination of the root cause of the anomaly that led to loss of the lander late in the EDL timeline; this knowledge will be essential for future landed missions.

While the loss of the lander during EDL curtailed Schiaparelli's surface mission, the planning and preparation for lander relay support from MRO, Odyssey, MAVEN, and MEX demonstrates important strategies for future international relay cross-support scenarios, including the value of thorough relay interoperability testing and the development of robust support plans addressing potential lander and orbiter contingency scenarios.

With the EDM mission complete, TGO now becomes an important part of the evolving Mars relay network. Current plans call for TGO to conduct a one-year period of aerobraking, beginning in April 2017, in order to achieve its final science orbit. Full science and relay operations are scheduled to begin in early 2018, with planned relay support to ESA and NASA landed spacecraft over TGO's operational lifetime.

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10. REFERENCES

[1] Fratacci, Olivier. "Exomars orbiter science and data-relay mission/looking for trace gases on Mars." *38th COSPAR Scientific Assembly*. Vol. 38. 2010.

[2] C. D. Edwards, "Relay Communications for Mars Exploration," *Int. J. Satell. Commun. Network*, **25** 111-145, 2007.

[3] C. D. Edwards, Jr, et al., "Relay Support for the Mars Science Laboratory Mission", IEEE Aerospace Conference, Big Sky, MT, March 2-9, 2013.

[4] "MRO Relay Telecom Support of Mars Science Laboratory, Surface Operations" D. Bell, S. Allen, N. Chamberlain, M. Danos, C. Edwards, R. Gladden, D. Herman, S. Huh, P. Ilott, T. Jedrey, T. Khanampornpan, A. Kwok, R. Mendoza, K. Peters, S. Sburlan, M. Shihabi, R. Thomas, IEEE Aerospace Conference, Big Sky, MT 2014.

[5] C. D. Edwards, Jr., et al., "Replenishing the Mars relay network." *Aerospace Conference, 2014 IEEE*. IEEE, 2014.

[6] Consultative Committee for Space Data Standards (CCSDS), "Proximity-1 Space Link Protocol – Physical Layer," CCSDS 211.1-B-3, http://www.ccsds.org, March 2006.

[7] Consultative Committee for Space Data Standards (CCSDS), "Proximity-1 Space Link Protocol – Data Link Layer," CCSDS 211.0-B-4, http://www.ccsds.org, July 2006.

[8] Consultative Committee for Space Data Standards (CCSDS), "Proximity-1 Space Link Protocol – Coding and Synchronization Sublayer," CCSDS 211.2-B-1, http://www.ccsds.org, April 2003.

[9] Charles D. Edwards, Jr., et al., "The Electra Proximity Link Payload for Mars Relay Telecommunications and Navigation," IAC-03-Q.3.A.06, 54th International Astronautical Congress, Bremen, Germany, 29 September – 3 October, 2003.

[10] E. Satorius, et al., "Chapter 2: The Electra Radio," in "Autonomous Software-Defined Radio Receivers for Deep Space Applications", http://descanso.jpl.nasa.gov/Monograph/series9/Descanso9_Full_rev2.pdf 2006.

[11] Allard, D. and R. Gladden, "Mars Relay Operations Service (MaROS): Managing Strategic and Tactical Relay for the Evolving Mars Network," 10.1109/AERO.2012.6187115 , IEEE Aerospace Conference, Big Sky, MT, 2012.

[12] "Mars Reconnaissance Orbiter Views Schiaparelli Landing Site," http://exploration.esa.int/jump.cfm?oid=58480, European Space Agency, 21 October, 2016.

[13] "Detailed Images of Schiaparelli and Its Descent Hardware on Mars," http://exploration.esa.int/jump.cfm?oid=58549, European Space Agency, 27 October, 2016.

[14] "Schiaparelli Crash Site in Colour," http://exploration.esa.int/jump.cfm?oid=58557, European Space Agency, 03 November, 2016.

[15] "Schiaparelli Landing Investigation Makes Progress", http://exploration.esa.int/jump.cfm?oid=58590, European Space Agency, 23 November, 2016.

11. BIOGRAPHY

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